What Undergraduates Think About Clouds and Fog

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ABSTRACT

Weather events are part of every student's experience, and are controlled by basic principles involving the behavior of matter and energy. Despite this, many students have difficulty explaining simple atmospheric phenomena, even after exposure to primary and secondary science curricula. This study investigated the level to which undergraduates understood the formation of clouds in the atmosphere, and how effectively they incorporated fundamental principles of matter and energy into their explanations. Interviews with earth science undergraduates at the University of Maine indicated that many had trouble with the correct identification of water in its different states, and were unable to name the sources of moisture in certain cases of cloud formation. If these misconceptions can be recognized and addressed directly by instructors, the potential exists to lead students to form better and more accurate mental models of weather.

INTRODUCTION

Clouds and precipitation are visible manifestations of the transition of water between its solid, liquid, and vaporous (gaseous) phases in the atmosphere. Phase changes are central to most meteorological phenomena, and are responsible for the atmospheric re-distribution of moisture and heat energy. The complete "water cycle", with the added terrestrial components of deposition, storage, and runoff, is a major driver of geological and climatic systems, and a cornerstone of the biosphere.

The relationships between matter and energy that underlie the water cycle are prominently addressed in state and national standards for science education. The National Science Education Standards (NSES, 1996) set goals for understanding "the properties and changes in properties of matter" along with "transfer of energy" and "structure of the earth system" as benchmarks for grades 5-8. For grades 9-12, the NSES address the "interactions of energy and matter", "geochemical cycles", and unifying concepts such as equilibrium. Throughout the standards, emphasis is placed on the study of fundamentals, and an approach to scientific phenomena that emphasizes systems rather than singular processes.

The Maine Learning Results (MLR), an evolving set of standards for pre-college education in the state where this study was conducted, speak explicitly to topics relating to matter, energy and the water cycle. MLR states that, by graduation from high school, students should:

- Illustrate the cycles of matter in the environment, and explain their relationship.
- Analyze how matter is affected by changes in temperature, pressure, and volume.
- Explain the relationship between temperature, heat, and molecular motion.
- Describe how air pressure, temperature, and moisture interact to cause changes in the weather.

These criteria suggest that, if the standards are maintained, undergraduates should matriculate with a scientifically correct view of how atmospheric processes work, and a notion of how earth systems are connected to the physical principles that govern them. Pursuant to standards like the NSES and MLR, college instructors assume that their students have been exposed, at least qualitatively, to the concepts of heat and temperature, molecular kinetics, and the primary states of matter.

Along with formal instruction, young people possess a lifetime of observational experience with the water cycle. They have all seen kettles boiling, bathtubs steaming, and the accumulation of clouds in the sky before a rainstorm. Many have noticed the coincidence of temperature change and precipitation, and the connections between wind, clouds, and weather. To the instructor, this suite of common examples represents a windfall of opportunity. Any classroom with a window and a thermometer may become a laboratory for the discussion of weather, a venue for developing real-time links between abstract principles and visible occurrences. With internet access, teachers wishing to leverage the atmosphere as a teaching tool now have a world of information at their fingertips.

However, personal experience suggests that these connections are not being made in many classrooms. Consequently, undergraduates struggle to form correct explanations of weather events, and are unable to connect theories of energy and matter with actual phenomena. I've noticed this frequently in my career as a captain of sail training vessels, and further observed that lessons on weather, when taught, often aren't retained. Topics related directly to the water cycle frequently seem most problematic. What's in a cloud? What is fog? Why do some clouds make rain, while others don't? Why can it get suddenly overcast in the evening at sea, a time of day when sailors traditionally get out their sextants in the hope of glimpsing a navigational star?

For this study, research questions were defined with the goal of learning more about how students approach the topic of clouds and weather:

1. What is the general level of understanding among college students regarding the water cycle and basic weather phenomena? Have they attained the level of preparation suggested by the learning standards?

2. What are the chief cognitive barriers to understanding the water cycle? Do they conform to past findings in the literature? Is it possible to identify any crux concepts, with their roots in the fundamentals of the hydrographic cycle?

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A REVIEW OF THE LITERATURE

Little exists in the literature to specifically address how students understand weather, particularly at the secondary and undergraduate levels. In an omnibus survey, Aron et al. (1994) cataloged a series of myths and misconceptions regarding the atmosphere, work that was cited by Henriques (2002) in her own literature review. Here, the latter acknowledged that much of what there is to know about how students view the atmosphere must be drawn from more generalized examinations of overarching concepts, like the water cycle.

The findings of such research indicate that phase change, rather like the physics of simple motion, is a subject area where individuals build explanations from a combination of observation and doctrine. Some of these combinations are correctly wrought, but others are not. Older individuals, with more formal training, are frequently more confused. Osborne and Cosgrove (1983) found wide disparities in the views of children about the nature of evaporation, and even less consistency with regard to condensation. The work of Bar et al. (1989, 1991, 1994) placed the cognitive progress of children's "water literacy" in parallel to the assimilation by the individual of other fundamental scientific concepts, most notably particle theory and the conservation of matter.

While a student may "learn" by rote explanation what clouds are made of, a complete understanding of this question hinges upon a correct model for how water moves between phases in the atmosphere. Because all students, merely by watching the weather, have built a long history of witnessing the water cycle in action, their cognitive models are likely formed by personal experience as well as by prior teaching (Taber, 1998). The everyday visibility of phase change sets it apart from many other chemical processes, and provides something of a two-edged sword to the instructor. The world is rich with examples, but a student's views are likely to be prejudiced by their own history of observation.

Given a constructivist approach to teaching, Bar et al. (1989) argued that productive formal instruction must be synchronized with recognized stages of cognitive development, and stress the series of important "accommodations" (Posner et al., 1982) with regard to the water cycle that take place between ages 5-12. Bar agrees with Posner's advocacy of relevant contextual examples. Students, she says, have no reason to prefer the correct scientific view if it contradicts their experience.

Osborne (1983) agrees that comprehension occurs more readily when visible examples of processes are available to students. As well as being intuitively palatable, this finding supports the conclusions of other authors about the challenge of understanding phase change. Osborne noted that students have the most difficulty with open systems, and remarked that one can't easily "see" transitions between liquid and vaporous states. Water vapor is invisible, and changes may take place very slowly.

Johnson (1998) noted that students thought differently about water processes at ambient temperatures than they did in cases where a direct heat source was present. Gopal (2004) explored the understanding of phase change and vapor pressure among students of chemical engineering, and noted the particular challenge posed by condensation. As with Ewing and Mills, (1994) Gopal discussed the intangible nature of condensation, and added that reciprocal processes are often given short shrift by texts and instructors alike.

TABLE 1. STUDENT SAMPLE COMPOSITION

Subject	Major	Year
J	Business/Agriculture	4
Z	Earth Science	3
T	Political Science	1
D	Computer Science	4
C	Education (History)	3
E	Biology	3

An alternative to reductive and context-poor science syllabi may lie in the use of natural systems as tools for integrating content with observations. This approach to teaching is advocated by the National Science Education Standards, and supported by the literature. Ben-Zvi Assaraf (2005) noted that students in a broad, context-based, unit on the water cycle showed a distinct improvement in their ability to form mental models of complex processes, and were better able to identify and anticipate relationships, than students taught in a purely topical format. The concept of reciprocal processes (Gopal, 2004) became clearer, as did the notion of cyclical ones. These revelations are meaningful from a teaching standpoint, as a large number of observable physical phenomena represent either equilibrium states or cycles, without clear start and finish points.

METHODS

In the spring of 2006, a study was conducted with University of Maine students to assess their understanding of evaporation, condensation, and cloud formation. ERS 140, "The Atmosphere", is an introductory earth science course at the University, taught annually to one section of 10 to 20 students, and presented as a mix of screen-based lectures, and laboratories. In labs, students use graphs and simple calculations to interpret weather data, obtained from local observations or the Internet.

At the time of the study, eight students were enrolled in ERS 140, about half of who were majors in the physical or natural sciences. The others were registered to fulfill a university distribution requirement for laboratory science. Six students agreed to participate in the study (Table 1).

Given the small sample size and a desire to obtain clear and nuanced answers from the subjects, an open-response interview method was chosen. Interviews were given early in the semester, at which point students had been exposed to a unit on the global heat budget and the water cycle, but had not yet discussed specific atmospheric features or weather events.

Questions for this investigation were designed to determine whether students' views of cloud formation were freighted with some of the cognitive challenges

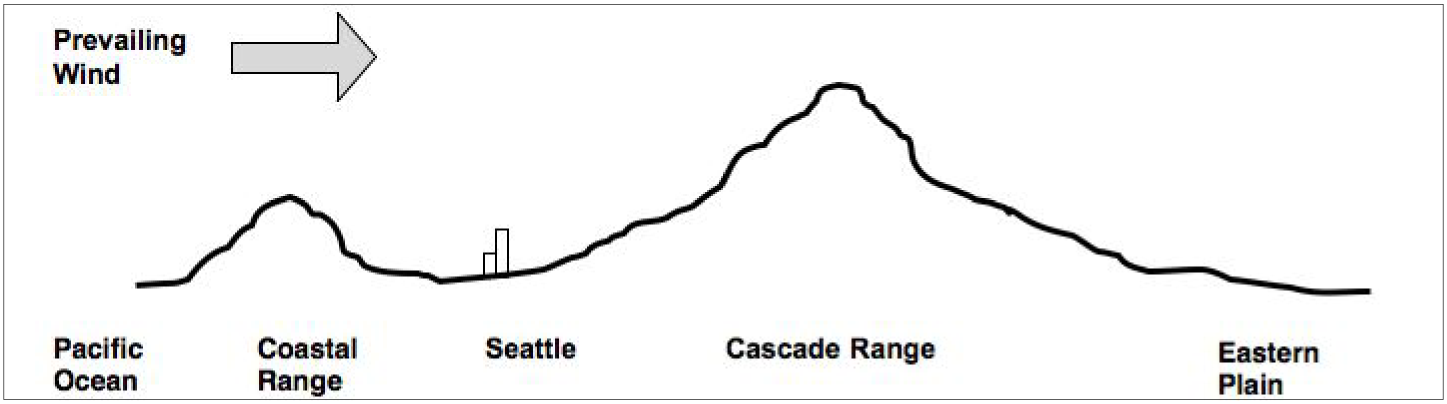

FIGURE 1. Facsimile of conceptual sketch used in support of question 1.

noted in the literature, most notably those of Johnson (1998) and Gopal (2004). Are evaporation and condensation in the atmosphere harder for students to model because they take place at ambient temperatures? Further, is the "invisible" process of condensation a challenge for students to accept? What casual observations have led to misassembled explanations? Finally, are any other "crux concepts" present, fundamental misunderstandings that form barriers to greater comprehension?

Interview questions were phrased as weather scenarios to encourage thinking about entire processes rather than discrete events. Two main question stems were developed, each conceived to address the core concepts of the hydrographic cycle: evaporation, condensation, temperature change, saturation, and equilibrium. "Branch questions," designed to measure specific understanding of key points, were also included.

Question 1: *"Consider the Pacific coastal city of Seattle. Seattle is famous for its rainy climate, while eastern Washington is a near-desert. Why is this the case?"*

This question was posed verbally, and then supplemented with a simple sketch showing the zonal geography of Washington state, including ocean basin, coastal mountain range, and inland plains (Fig. 1). The aim of this question was to give students the chance to recognize oceanic evaporation as a primary source of atmospheric moisture, and to note lifting as a main mechanism for cooling and condensation. I was curious to see how aware students were of the extent to which air masses could be altered by topography, and to ascertain their understanding of the relationship between the temperature of an air mass and its capacity for water vapor. Finally, students were encouraged to discuss the thermodynamic mechanisms behind temperature change in the atmosphere.

Question 2: *"Which of the following would you expect to produce fog, and why?"*

a. warm air moving over cold water
b. very cold air moving over cold water
c. warm air moving over warm water
d. cold air over warm ground

Question 2 was designed to look directly at how students viewed the mechanisms of evaporation and condensation, and to measure their visualization of water in its liquid and gaseous states. The geographical context for this question was more local. Maine is a rural state with an extensive maritime coastline, and many lakes and rivers. Despite large seasonal variations in air temperature, oceanic and inland water masses tend to remain fairly cold. This combination leads to frequent instances of fog, from a variety of mechanisms.

As with Question 1, the verbal query was supplemented by a sketch (Fig. 2). Among the answers, all but "c" represent cases for one of the three main categories of fog. In each, the mechanism provides a chance for students to explain how water vapor is taken up by the air column, and when it may be released as liquid condensate.

Answer "a" represents the most common cause of summer fog over cold bodies of water. Warm air, with a large water vapor content, is advected over cold water, and the layer of air near the surface is cooled below its saturation temperature. At this temperature, known to meteorologists as the 'dew point," a portion of the water vapor is released as condensation, forming fog.

Answer "b" describes a common wintertime scenario in Maine harbors, and on a river that runs through the University of Maine campus. Here, a layer of frigid arctic air sits over water that is just above freezing. The water, in this case warm relative to the air, is evaporating. A portion of the vapor then condenses as droplets, or "steam" before being re-evaporated. A key conceptual difference between answers "a" and "b" is the source of the condensate. In "a," fog has condensed from ambient water vapor within an air mass, while in the case of "sea smoke," the water for the cloud is being generated by the water mass.

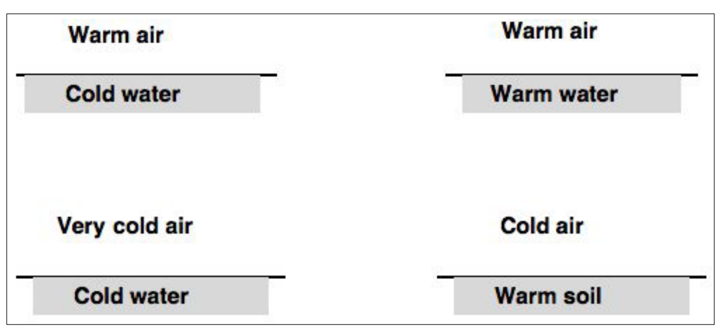

FIGURE 2. Sketches of air and surface profiles used in support of question 2.

from warm liquids. The cases of "sea smoke" and "ground fog" are examples of this, where convection causes warm, moist air to rise and cool, releasing vapor as condensate. However, an excerpt from another interview shows a reluctance to broaden this concept to include a case on a winter day where a body of seawater, though too cold for swimming, remains quite warm in comparison to the air:

I: So you have very cold continental air moving over the Gulf of Maine, which is...
C: 33 degrees?
I: Yeah, not much colder than that.
C: So there's a temperature difference… I don't think there'd be enough to create fog. I'm basing this on experience, not on something technical.
I: Sure.
C: So when it's below zero out, there's no clouds, it's really, really dry, you're chapped…
I: Why do you think that is?
C: Well, we've talked about temperature differences, and moisture in the air, so, the warm air with moisture in it touches cold air, that's when it will go from the vapor state to the liquid state, which we can see. So, if it's really cold, I'm thinking, maybe the air has no moisture in it.

(Here C has correctly recognized the relationship between temperature and the potential of air to hold moisture.)

I: So if we talk about the sea surface, liquid water, which can't be any colder than say, about zero C, with the very cold dry air over it, what's that boundary going to look like? We've talked about gradients… what are gradients in temperature and moisture going to look like? Give a little thought to what's going to happen in the boundary layer here.
C: The thought that I have, if the air is colder, it, has less stored energy… it doesn't have the ability to pull moisture off the water.

However, in this last exchange, C reiterates the conviction that evaporation must be driven "from above." As with the warm-air-over-cold-water scenario proposed by D's thinking in the previous excerpt, C is suggesting that fog must be produced by air "pulling" vapor from the surface.

Inherent in these examples is confusion about the difference between the gaseous and liquid states of water, and a well-entrenched misunderstanding that water vapor is visible to the eye, at least sometimes. This misconception seems to block understanding of where and when phase changes are taking place.

I: OK, what do you think of when you're looking at a cloud?
D: Air and water vapor... air, with water trapped in it. When I was younger, I thought of it as actual physical droplets... but now, after chemistry class, I think of it as how you can saturate one liquid with another. I think of them both as gasses, saturating one another.
I: OK.
D: Vapor is a gas, and air is a gas, so they can be combined, like you can combine liquids.
I: Any sense of why some clouds have rain under them, and some don't?
D: That... seems to have to do with the kind of temperature change a cloud is going through, and how much moisture is actually in it. Like, think of chemistry. If you're adding salt to water, like the vapor is the salt, you're adding it in until it reaches the point where you just can't add anymore in, and then if you were to strain that out, you'd get salt.
I: OK
D: The water just can't take any more soluble salt. That's how I saw it.
I: So, like a saturation point?
D: Right. The cloud gets saturated to a certain point, it just can't take anymore… and, that depends on temperature, like, I know that if you heat up a solution, it can take more salt. A cloud, it's the same thing, if you heat it up, it can take more moisture, depending upon where you are in the atmosphere. They do move up and down. Like a cloud is OK at one level, but if you move it, change its level, it cools off and can't hold as much moisture.
I: OK.. What is your sense of what fog is?
D. It's essentially a cloud, just lower... kind of like, just, water vapor, caught up in air. And it's got a high enough ratio of water vapor to air so that it's actually visible… or somewhat tangible.
I: So it's like a cloud, sitting on the ground?
D: Yeah.

D is a fourth-year computer science major who has taken general chemistry. In these examples, D draws on his experience with solutions to explain the behavior or water vapor in clouds. However, while he has correctly described the concept of "saturation", he has applied it in the wrong place. A cloud already represents air that is beyond saturation with regard to moisture. This is a confusing concept to students. The fact that not all clouds yield tangible evidence of liquid water in the form of rain suggests to them the existence of some intermediate phase of water that is not really there.

Another student, Z, is a third-year earth science student who has a nearly correct view of cloud composition:

I: What is the composition of a cloud?
Z: Water vapor, necessary for condensation, water droplets, ice, if it's cold enough, smoke, if the particles are small enough... you have solutions, like smog. There have to be water droplets, since the rain has to come from somewhere.
I: If a cloud has water droplets in it, is it always raining when it's cloudy?
Z: Um, it depends on the differences in the water droplets.
I: So what would the differences need to be? It's cloudy outside today, but we didn't get wet on the walk over here. Why?
Z: Well, if the cloud is large enough to hold its vapor until… Rain clouds are large clouds where the water vapor all comes together and condensing into larger and larger droplets until they are too large to be suspended until they begin to fall.

This is correct. But Z remains unclear on the *appearance* of different phases of moisture, incorrectly attributing a conditional visibility to water vapor.

I: Which of those can you see? Can you see water vapor?
Z: In certain conditions, like if it's cold outside and you breathe… You see your breath, cause it takes less water vapor to make a cloud when it's cold. On a warm day, you don't see it, because the vapor is absorbed by the air.

In this exchange, Z is explaining that your breath on a cold day is somehow "excess" water vapor that the air can't "hold". Yet it remains "vapor" in this student's mind, apparently because it remains airborne. This erroneous view might be described by the assertion that "all airborne water is vapor". This confusion appears to be common, and may explain why none of the answers to question 1 included a step where clouds were re-evaporated as air descended from the mountains (Table 2). If a cloud is already envisioned as "vapor", then no

TABLE 2. ANSWER DISTRIBUTION (QUESTION 1)

Subject	Major	Marine Evaporation[1]	Orographic Lifting[2]	Cooling Mechanism[3]	Identifies Condensation[4]	Eastern Desert[5]
J	Business	Y	Y	Not specific	Y	Precipitation west of mountains
Z	Earth Science	Y	Y	Adiabatic cooling	Y	Precipitation west of mountains
T	Political Science	Y	Y	Not specific	Y	Precipitation west of mountains
D	Computer Science	Y	Y	Adiabatic cooling	Y	Precipitation west of mountains
C	Education	NR[6]	NR	NR	NR	NR
E	Biology	Y	Y	Not specific	Y	Precipitation west of mountains

Notes:
[1]Student identifies maritime evaporation as primary source of moisture
[2]Student notes topography as mechanism for lifting air mass
[3]Mechanism for cooling of air mass as given by interviewees
[4]Condensation is identified as source of clouds and rain
[5]What explanation is provided for dry zone east of mountains?
[6]NR=No response recorded

Answer "d" describes a mechanism closely related to that for "sea smoke", but where a warm mass of earth is substituted for a body of water. As the ground cools by radiation, a rising current of warm air carries water vapor that is condensed when the dew point is reached.

Interviews were conducted by the author with individual students, and were recorded with a portable cassette machine. Sessions took between 30 and 60 minutes. Subsequently, the interview tapes were transcribed and reviewed by the author. A table was prepared (Tables 2 & 3) to record the general distribution of answer types among interview subjects.

RESULTS AND DISCUSSION

Answer data from question 1 (Table 2) show that all students correctly noted that water evaporating from the ocean was the source of rain in Western Washington. All agreed that rain was the result of condensation as vapor-laden air moved east over the mountains and cooled. The three subjects with collegiate science experience had a specific idea of the relationship between temperature and pressure that causes rising air to cool. The two others who answered this question had a sense that "higher was cooler", but offered no mechanism beyond that as an explanation. Finally, all attributed the dryness of eastern Washington to a "wringing out" of moisture by the mountains, though none offered the more complete explanation that the air mass might also re-evaporate water as it descended and became warmer.

Data from question 2 (Table 3) indicate that all subjects correctly thought warm air over cold water to be a likely scenario for fog. However, only two of the six (both science majors) made the correct observation that the fog was condensing from the air column, rather than evaporating from the surface. Only two students were able to recognize either of the other correct answers. All but one thought that water vapor was part of what you saw in a cloud, and all said that water vapor was visible "sometimes".

Excerpts from the interview transcripts support several findings from the literature; most notably that students often do not visualize condensation as clearly as they do evaporation, (Bar, 1994), and that reciprocal processes (e.g., condensation vs. evaporation) are often not well linked in the cognitive process (Gopal, 2004). As noted above, there was also a common (but incorrect) belief among the subjects that water in its vaporous state could sometimes be visible to the eye. Finally, as shown by Table 3, column 3, there was general difficulty in recognizing the ambient presence of water vapor in an air mass.

Students had distinct difficulty with the concept that airborne water vapor can serve as a source of condensation. Instead, they felt the need for a nearby reservoir of liquid water to get things started. Most picked "a" as a correct answer, but balked initially because cold water "lacks the evaporative energy" needed to make water vapor. Though several had experience with this type of fog, they could not explain the mechanism.

Examples from the transcripts illustrate these deficiencies. The interviewer, "I", is the author. Different subjects are shown by initial (C, B, Z, etc.):

I: Let's talk about fog now... (sketching) what I've drawn here is a series of lines that represent an air/water boundary…

D: Well, if this was water, this is air... (pointing) if water were a lot colder, enough so that when the air goes over the water, it wants to balance the energy as much as possible, so the heat goes from the air into the water, it makes the water begin to evaporate. And we get the fog, that's water vapor that's coming off the water, that's beginning to evaporate. When the air goes over the water, it wants to balance the energy as much as possible, so the heat goes from the air into the water, it makes the water begin to evaporate. A lot of times, you can get fog when the air isn't so warm that it can absorb a ton of moisture, and instead the water vapor, it's going to come up and just kind of hang over the water.

This explanation categorizes fog as water vapor that has been evaporated from the surface, but that the air is not energetic enough to absorb. D is confronting two conceptual obstacles here. First, the subject is considering water vapor to be visible, at least while in some intermediate stage before it is fully evaporated. Second, he is failing to recognize the air column itself as a potential source of water, and to see that the condensing of fog may be the reciprocal process of an evaporation that took place at some other place and time.

The literature (Bar, 1989; Gopal, 2004) suggests that this bias may be the result of observation, as most students have witnessed "fog" in the form of steam, rising

TABLE 3. ANSWER DISTRIBUTION (QUESTION 2)

Subject	Major	Warm Air Over Cold Water	Very Cold Air Over Cold Water	Warm Air Over Warm Water	Plowed Fields at Night	What's in a Cloud?	Is water vapor visible?
J	Business	Warm air evaporates the cold water and makes fog.	No	No	No	Water Vapor or Ice Crystals	Sometimes
Z	Earth Science	Water cools air and triggers condensation.	No.	No	No	Water droplets and/or ice crystals	Sometimes
T	Political Science	Warm air evaporates the cold water and makes fog.	Maybe. Warm water evaporates and makes fog.	No	No	Water Vapor and Water Droplets	Sometimes
D	Computer Science	Warm air evaporates the cold water and makes fog.	No. Cold air is too cold to evaporate the water	No	No	Air and water vapor	Sometimes.
C	Education	Warm air evaporates the cold water and makes fog.	No. Cold air is too cold to evaporate the water.	No	Cold air condenses moisture evaporating from soil.	No response recorded	Sometimes
E	Biology	Water cools air and triggers condensation.	No.	Yes. Warm water evaporates into the warm air.	No	Water Vapor. Ice, Water Droplets	Sometimes

further evaporation is possible.

T is a first-year humanities major who took chemistry in high school, and whose answer to question 1 demonstrates a sophisticated view of cloud formation. T does not invoke the principle of "saturation", but correctly outlines a process of evaporation, transport, and condensation.

I: Do you have any sense of what happens to the water between this stage (west of mountains) and this point (east of mountains)? Here, (west) the moisture is in the air, but up here, it gets to a state where you can see it, feel it. What has happened to cause this?
T: Well, it's like a water vapor. Evaporation, and then condensed into a liquid right there, makes it rain.
I: Ok, so the clouds are the product of the condensation. But you're not really sure of why that happens, other than that the cooling of the air is something that encourages the condensation?
T: Yeah.
I: So what's in a cloud?
T: Water vapor, water droplets.
I: By water droplets, you mean liquid water?
T: Yeah, condensing water, because that's where it changes from a gas to a liquid.
I: So, if you are looking out the window at a cloud, what would you say are the components of a cloud?
T: Mostly, ah water vapor.

In addition to this persistent conviction that clouds are mostly "water vapor", T is unsure of why phase changes are connected to temperature and energy:

I: OK, what is it about warm air that allows it to hold more moisture?
T: I'm not really sure about that.
I: Ok, So the clouds are the product of the condensation, but you're not really sure of why that happens, other than that the cooling of the air is something that encourages the condensation.
T: Yeah.

Four of the six interview subjects were unable to consistently identify airborne water vapor as a source for condensation. Instead, they appeared biased towards evaporation as a mechanism, where a temperature gradient between air and water draws water vapor off of a liquid surface. This bias may be driven by observational experience with "steaming bathtubs" and other vessels of warm liquid (as described by Bar, 1989), though the temperature gradient in those examples is going in the opposite direction.

Where a liquid surface is present, most students look for a way to name it as the source of the "cloud", regardless of the relative temperature characteristics of air and water. Question 1, with the Pacific Ocean standing by as a very conspicuous source of water, vapor posed less of a challenge than question 2, where the presence of water vapor in the air was implied rather than demonstrated.

Confusion also existed over just which phase of water is actually represented by clouds, perhaps because not all clouds are coupled with precipitation. Many students attempted to classify all airborne water as "vapor", whether it is visible or not. Again, this may be influenced by experience. Clouds are visible, yet they frequently don't yield rain at the surface, so they must (students think) be vapor. Your breath, visible on a cold day, has come from your lungs as a gas, so any water it contains must be vapor. "Saturation", where mentioned, was named as the point where water vapor becomes visible, but not necessarily the occasion of a phase change from gas to liquid.

The two subjects majoring in earth and life science provided the most correct and complete answers to both questions, indicating that a longer and more rigorous exposure to concepts relating to the water cycle has led to better comprehension. This elevated level of initial literacy may also have nourished a more compete assimilation of topics introduced during the first unit of ERS 140.

CONCLUSIONS

This investigation indicates a limited understanding among its subjects regarding the processes of evaporation, transport, and condensation that produce clouds and precipitation in the atmosphere. While interview data yielded by the survey were complex, two consistent conceptual shortcomings were observed. First, all of the subjects failed to note that water is always invisible in its vaporous state. Second, four of the six subjects had difficulty recognizing airborne water vapor as a source of cloud condensate. The prevalence of these two misconceptions amidst this small but relatively diverse sample suggests that they may be common in a broader context. The development and distribution of a quantitatively scored survey instrument would allow for a statistical test of this hypothesis.

While the national and state standards specify coverage of the properties of matter, the water cycle, and earth systems at the primary and secondary levels, the data from this study indicate a low level of prior exposure to this material, at least in any way that has led to a durable retention of correct models. This finding supports the conclusions of earlier authors (Aaron et al., 1994; Henriques, 2002) that the treatment of atmospheric topics at the primary and secondary levels is lacking.

Results from this study also support the findings of Gopal (2004) and Johnson (1998) regarding the cognitive difficulties posed by condensation at ambient temperatures. The failure of students to recognize airborne water vapor as a source of cloud condensate generates models that rely too heavily on temperature gradients and liquid surfaces as mechanisms, and limits the ability of students to recognize the transport of water vapor in atmospheric systems.

Subjects of this research frequently misidentified cloud condensate as "water vapor', a shortfall that hampered recognition of the gas-to-liquid phase change that characterizes condensation. This mistaken notion that "all airborne water is vapor" seems well entrenched in the minds of many students, and stands as a direct obstacle to recognizing when phase changes take place, and what conditions that are necessary to produce them.

Instructors who seek to foster a sound understanding of cloud formation should remind students that water vapor is nearly always present in the air column, and that it is invisible. In addition to providing examples that illustrate the water cycle in its entirety, cases should be chosen that force pupils to consider the availability of water from the atmosphere, even when a local source of liquid water is not apparent. This should encourage the consideration of moisture as one of the characteristics of an air mass, and prompt students to consider what might result as conditions of temperature and pressure change.

At all levels of instruction, the value of earth systems as a pedagogical framework for scientific principles should be considered. In particular, teachers who are discussing the properties of matter, and the relationships between the phases of matter and the presence of energy should recognize the teaching example that is provided by clouds and weather events, and leverage it accordingly.

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